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Effects of wave function modulation on high-frequency carrier transport in quantum wells under high biasing field

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Abstract The effects of wave function modulation on the high frequency response of GaAs/AlAs quantum wells with several thin barrier layers being inserted inside the wells are studied. Carrier scattering by longitudinal optic phonons, deformation potential acoustic phonons and background-ionized impurities are considered. The wave function modulation induced inside the quantum well is found to reduce the scattering strength and reduces the ac mobility normalized by the dc mobility because the enhancement rate of dc mobility is much higher than the ac values. The variation of ac mobility normalized by dc mobility with the frequency of the applied field is found to be fairly constant upto a certain frequency beyond which it drops down

Keywords Wave function modulation, quantum wells, carrier transport, carrier scattering, optic phonons

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1. Introduction

Mobility of electrons has become the key feature of high speed electronic circuits. Speed of computers and communication equipments has been the fascinating feature now -a-days due to the development of very fast switching semiconductor devices. Since the response of the system depends on the motion of the conduction electrons of the devices used in the systems, the extensive study of mobility of charge carriers in the device has been found essential in the context of today's growth in the field of electronics. The said fact has made the researchers of this field to realize that high electron mobility is one of the most challenging area in the field of semiconductor physics and is important for special device applications. All these have motivated the present author to study the effects of wave function modulation on high-frequency carrier transport in quantum wells under high biasing field. In recent years, low-dimensional structures such as quantum wells (QWs), quantum dots, quantum wires (QWrs) have been actively studied [1-4]. The reduction of spatial dimensions will influence the efficiency with which electron can interact with the phonons. The remarkable advancement in the techniques of crystal growth such as fineline lithography, metalorganic chemical vapour deposition (MOCVD) and molecular beam epitaxy (MBE) has stimulated active research on quasi low dimensional electron transport in quantum wells and quantum wires of channel width comparable to electron de-Broglie wavelength [5,6]. These structures are often referred to as quasi-low dimensional structure (LDS) or nanostructure. They posses radically different properties for those of bulk semiconductor because they quantum mechanically restrict the degrees of freedom of the conduction electron to two or one. This produces fascinating changes in electronic, magnetic, optical and vibrational properties [7,8]. A thin layer of a lower bandgap semiconductor like (GaAs) sandwiched between the layers of a higher bandgap material (like AlGaAs) forms a quantum well (QW). In the quantum structures, the density of states and scattering rates of the carrier are different from those in the bulk material. In QWs, modulation doping separates the electron from their parent donor atom reducing thereby the influence of ionized impurity scattering [9,10]. Therefore, the electron mobility is high, particularly at low temperature where the longitudinal optic(LO) phonon scattering is insignificant. The electron in the potential well of the abrupt heterojunction are separated from the donor atoms, but are still close enough to be subjected to a Coulomb attraction. A thin layer of undoped AlGaAs can be placed between the doped AlGaAs and the undoped GaAs to increase the separation between the carriers and the ionized donors thereby increasing further the electron mobility because of less Coulomb interaction. Quantum structure thus shows promise for application in fast miniature devices. Some of the unusual properties of LDS's like quantum Hall effect have received much attention in recent years.

Investigation on electronic transport in quantum structure is extremely important for an understanding of the carrier kinetics under confined condition. Such studies also help in optimizing the performance of the structure in device and in exploring the possibilities of new applications. LDS's are useful for millimeter and sub-millimeter wave application because they can respond very quickly and sensitively to voltage control. In addition, they have potential advantages which make them attractive for nonlinear function. These considerations have motivated us to study carrier transport in semiconductor quantum structures. The modulation doping technique is one of the most successful example that worked well at high frequency [11]. Wave function manipulation is also relevant for the worldwide efforts to fabricate SiGe p-channel metal oxide semi-conductor (PMOS) device of enhanced carrier mobility as compared to Si PMOS. Hot electron conditions are developed if the applied electric field is sufficiently high so as to cause a pronounced deviation from ohm's law. At these fields, the drift energy of the electrons may be compared to the thermal energy and the symmetric term is no longer the equilibrium distribution at the lattice temperature. The average electron energy is also much higher than that in thermal equilibrium with the lattice. The whole character of the electron transport may change radically at such high electric energy.

In the present work, we have investigated the high frequency response of GaAs/AlAs QWs with several thin barrier layers being inserted. The scattering strength is found to reduce significantly due to wave function modulation created by such thin multiple barrier layers. The presence of hetero-interfaces creates phonon modulation and reduces the effect of carrier scattering by LO phonons *via* polar coupling, acoustic phonons *via* deformation potential coupling and background-ionized impurities are incorporated. The effect of piezoelectric scattering is insignificant compared to other scattering mechanisms and hence not included in the calculations [12].

In semiconductor physics, realization of high electron mobility is very challenging and it is important for device application. Our aim is to propose a method to increase the electron mobility by the modulation of wave function along the direction perpendicular to the layers and demonstrate the mobility enhancement by numerical calculations.

Polar optic phonon scattering is the most important mechanism that limits the electron mobility at room temperature. In a modulation doped heterostructure, optical phonon can be strongly modified by the presence of hetero-interfaces [12-16]. Reducing well thickness, it is also possible to reduce optical phonon scattering.

It is known that the scattering strength decreases with increasing layer thickness in GaAs/AlAs quantum wells as long contribution from inter-sub-band structure is negligible [16]. Scattering strength is more sensitive to the electron wave function than the phonon modulation so the effect of scattering is reduced due to modulation of the electron wavefunction

In the present work, the electron mobility of GaAs/AlAs quantum wells with several thin barrier layers being inserted is calculated numerically. The scattering strength is reduced due to wave function modulation induced by such thin barrier layers [17]. Although phonon spectra are modified in QW [18] as long as QWs are not too narrow, consideration of only bulk mode phonon gives result agreeing with that obtained by considering both the interface and the confined phonons for a GaAs QW [19]. The consideration of bulk mode phonons only in this system is not expected to yield serious error. In fact, calculation of ohmic mobility with bulked phonons agrees with the experimental data [19]. Thus we take here bulk mode phonons which simplify the expressions for scattering rates The effect of carrier screening for LO phonon is insignificant over the temperature range of investigation [20], and so it is not incorporated in our present calculations. However, the screened scattering rates for other scattering processes are considered the carrier scattering rate with screening, where necessary, are obtained from Ref. [7].The scattering rates for acoustic deformation and ionized impurity scattering are obtained from Ref. [7].

2. Theory

Two quantum structures of square cross section are considered Out of them, one is a single quantum well (QW) of GaAs (Al,Ga)As, and the other one is a single quantum well (QW) of GaAs within which thin layers of AlAs are inserted and is denoted as wave function modulated QW (WFMQW). We consider square QWs of infinite barrier height with a channel length Lz. Three thin barriers of AlAs with equal thickness much less than Lz are inserted at equal spacing. These barriers modulate the electron wave function so that it has an appreciable amount of short wavelength component. In the numerical calculation, we have estimated the effect of the inserted barriers by incorporating the scattering rates of AlAs and subtracting the same of GaAs for that position of the barriers.

In QWs, there is a significant reduction in the effect of ionized impurity thereby improving the carrier confinement, establishing a strong electron-electron interaction within the channel. This interaction in energy and momentum exchange favours a heated drifted Fermi-Dirac distribution function for the carriers characterized by an electron temperature T_e and a drift crystal momentum p_d. In the presence of an electric field F applied parallel to the interfacial planes, the distribution function $f(k)$ of the carriers with energy E is written as

$$f(k) = f_0(E) + (h) p_d \, k / m^* \left(-\partial f_0 / \partial E\right) \cos\theta \,, \qquad (1)$$

where $f_0(E)$ is the Fermi-Dirac distribution function for the carriers characterized by an electron temp T_e, $\boldsymbol{p}_d$ is the crystal momentum, $\boldsymbol{k}$ is the (2D) wave vector of the carriers with energy E, m^* is the electronic effective mass and θ is the angle between the electric field $\boldsymbol{F}$ and 2D wave vector $\boldsymbol{k}$.

A composite electric field F consisting of a *dc* part F_0 and a ac part of magnitude F_1 and angular frequency ω is applied parallel to the heterojunction interfaces so that the net field is thus.

$$F = F_0 + F_1 \sin \omega t. \tag{2}$$

The electron temperature T_e, and the drift momentum p_d, will have the similar components with the alternating ones generally differing in phase. So we write

$$T_e = T_0 + T_{1r} \sin \omega t + T_{1i} \cos \omega t\ , \tag{3}$$

$$p_d = p_0 + p_{1r} \sin \omega t + p_{1i} \cos \omega t\ . \tag{4}$$

T_0 is the steady part of electron temperature T_e. T_{1r} and T_{1i} are respectively the real and imaginary parts of electron temperature. p_0, p_{1r} and p_{1i} have the same significances like electron temperature.

The expression for the scattering rates of the LO phonon emission and absorption, respectively, are

$$1/\tau_e(E) = (\alpha\omega/II)(N_q + 1) \int_{d\phi} [q+(E,\phi) I_{2D}[q+(E,\phi), L_z]$$

$$\cdot q\ (E,\phi)\ I_{2D}[q_-(E,\phi), L_z] / [\sqrt{\ }\{E/(h\omega)\} \cos^2 \phi - 1]]$$

$$[1 \quad fo(E - h\omega)/1 - fo(E)][(-q \cos \phi \sqrt{h/\omega})/(\sqrt{2}\, mE/h\omega)], \tag{5}$$

$$1/\tau_a(E) - (\alpha\omega/II)\ N_q \int d\phi\ A_+\ [q_+(E,\phi), L_z]$$

$$[1 \cdot\ f_0 (E + h\omega)/1 - f_0(E)], \tag{6}$$

where $A_+ [q_+(E,\phi), L_z] = [q_+(E,\phi) I_{2D} [q_+(E,\phi), L_z] /$

$$\sqrt{\{E/h\omega\}} \cos^2 \phi + 1]][(-q \cos \theta \sqrt{h/\omega})/(\sqrt{2}\, mE/h\omega)]$$

ϕ is the angle between 2D wave vector $\boldsymbol{k}$ and phonon wave vector $\boldsymbol{q}$. Other symbols have the same significances as in Ref. [7]

The expression for the dc and the ac mobilities are computed here by solving the energy and momentum balance equations for the carriers and using the expressions of F, T_e, $\boldsymbol{p}_d$, and the carrier distribution function.

3. Results and discussion

Numerical results are computed for quantum well of GaAs with three AlAs layers inserted inside the GaAs quantum well. The widths of the AlAs layers are the same and is equal to 11.3°A typical background ionized impurity concentration of 6 X10[21] / m[3] and a biasing field of 1 X10[5] V/m are taken in the present calculation for lattice temperatures of 300K and 77K. The ac mobility is found constant upto 80 GHz beyond which ac mobility falls with the increase of the applied field. At low frequencies where the field does not change appreciably during successive collisions, the ac mobility remains constant. But at high frequencies, the field changes appreciably between consecutive collisions, decreasing the ac mobility. The variation of ac mobility normalized with dc mobility with the frequency of the applied field is shown in Figure 1. The solid curves indicate the results with inserted layers and dotted curves are for quantum well without inserted layers [7].

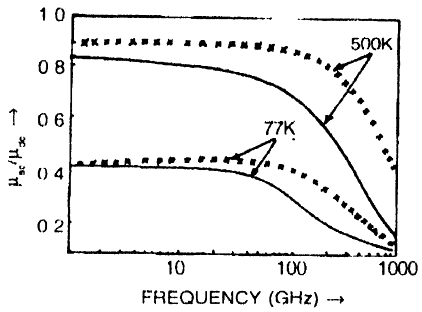

Figure 1. Variation of μ_{ac}/μ_{dc} with the frequency of the applied field for 77K and 300K for a typical channel length of 100nm. Carrier concentration of 2X10[15] /m[2] and dc biasing field of 1X 10[5] V/m The solid curves depict the result with inserted layers and non solid curves are without inserted layers

Figures 2A and 2B depict the variation of dc mobility with the channel width of the QW for lattice temperature of 300K [Figure 2A] and 77K [Figure 2B]. For a particular lattice temperature, four different curves are drawn. The solid curve gives the result with inserted layers following our model. The dashed curve represents the results obtained from Ref. [16]. The dashed-dotted curve depicts the results with single quantum well without inserted layers following Ref. [16]. The

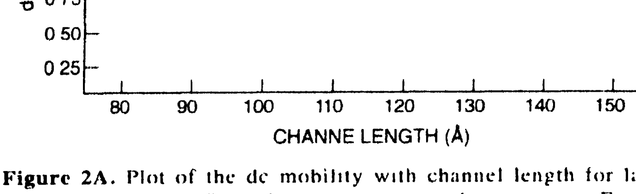

Figure 2A. Plot of the dc mobility with channel length for lattice temperature of 300K The other parameters are the same as in Figure 1. The solid curve gives the result with inserted layers following our model The dashed curve represents the results obtained from [12] The dashed-dotted curve depicts the results with single quantum well without inserted layers following [12] The dotted curve shows the results obtained from [7].

dotted curve shows the results obtained from Ref. [7]. The mobility is found to be lower in our case compared to Ref. [16]. This is because we have incorporated the acoustic and impurity scattering in addition to the LO phonon scattering and used the effective mass correction. The mobility is lower at higher temperatures as shown in Figure 2. This is quite normal situation [7]. In our earlier case [7], we got lower value of mobility. Both dc and ac mobilities are found to show much higher values compared to the GaAs quantum well without such wave function modulation. The mobility values are found to be slightly lower than that obtained by Takuma Tsuchiya and Tsuneya Ando [16]. In their computation, they neglected all the scattering mechanism except due to LO phonons. This implies that the wave function modulation surely enhances the mobility thereby promising the possibility of high-speed devices.

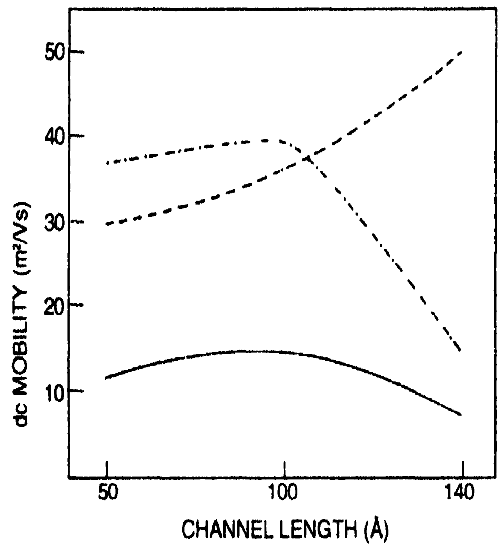

Figure 2B. Variation of dc mobility with channel length at 77K with the parameter of Figure 2A. The curves have the same significance as in Figure 2A

4. Conclusion

In the present study, we have investigated the high frequency response of GaAs/AlAs QWs with several thin barrier layers of AlAs being inserted. The wave function modulation induced inside the quantum well is found to reduce the scattering strength and enhance considerably both ac and dc mobilities significantly. But enhancement is much more pronounced in the dc values compared to ac values, thereby reducing the mobility ratios. The dc mobility values are found to be slightly lower than that obtained in Ref. [7]. The model is over-simplified in Ref. [16] in the sense that the contribution of impurity and acoustic scatterings are not included in the calculations. In the present study, the fall of ac mobility is faster than our earlier studies without the insertion of layers [7]. This implies that although the insertion of AlAs layers improves the mobility thereby improving the speed of the system, but the faster falling rate indicate that the frequency response is less flatter compared to our earlier work [7].

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